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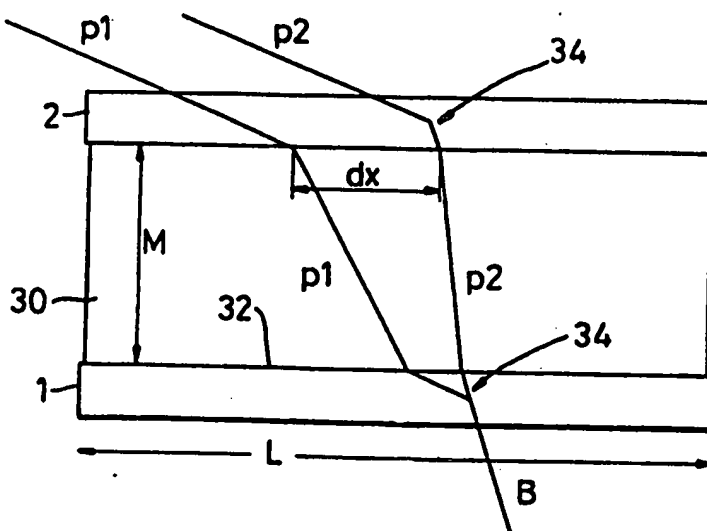
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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : <b>G02B 5/32, 5/18</b>	<b>A1</b>	(11) International Publication Number: <b>WO 97/22022</b> (43) International Publication Date: 19 June 1997 (19.06.97)
(21) International Application Number: <b>PCT/GB96/02970</b> (22) International Filing Date: 2 December 1996 (02.12.96) (30) Priority Data: 9525103.9 8 December 1995 (08.12.95) <b>GB</b> (71)(72) Applicant and Inventor: <b>STRACHAN, John, Scott</b> [GB/GB]; 6 Marchhall Crescent, Edinburgh EH16 5HN (GB). (74) Agent: <b>MURGITROYD &amp; COMPANY</b> ; 373 Scotland Street, Glasgow G5 8QA (GB).		(81) Designated States: <b>AL, AM, AT, AU, AZ, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, US, UZ, VN, ARIPO patent (KE, LS, MW, SD, SZ, UG), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).</b>  <b>Published</b> <i>With international search report.</i> <i>Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i>  <b>BEST AVAILABLE COPY</b>

(54) Title: HOLOGRAPHIC OPTICAL DEVICE AND METHOD OF MANUFACTURE



(57) Abstract

The invention provides an optical element comprising a first hologram (1) and a second hologram (2) separated by an intervening medium (30). The holograms (1, 2) have the same diffraction spacing and refractive index, but the first hologram (1) has an efficiency about one-half that of the second hologram (2), preferably about 50 % and >95 %, respectively. The geometry and the refractive index of the intervening medium (3) are such that an input beam (B) of mixed light undergoes diffraction and refraction to produce output beams (p1, p2) which combine in a controllably self-cancelling manner. Methods for the production of this element are also described.

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1

2     **TITLE OF THE INVENTION**

3

4     **HOLOGRAPHIC OPTICAL DEVICE AND METHOD OF MANUFACTURE**

5

6     **FIELD OF THE INVENTION**

7

8     This invention relates to optical devices for producing  
9     non-fringing destructive interference of light, and to  
10    a method of making and using the same.

11

12    **BACKGROUND TO THE INVENTION**

13

14    Light moves through space as an electromagnetic wave.  
15    The wave can be envisioned as a series of peaks and  
16    troughs moving continuously along a given path at a  
17    given frequency. Interference occurs when two waves  
18    pass through the same region of space at the same time.  
19    Interference between waves can be both constructive and  
20    destructive. Constructive interference occurs when the  
21    peaks (and troughs) of two waves meet each other at the  
22    same time and overlap. These waves are said to be in  
23    phase and when this happens the amplitude of the waves  
24    at the point of overlap is increased.

25

26    Destructive interference occurs when the peaks of one  
27    light wave meet and overlap with the troughs of a  
28    second light wave. When the peaks and troughs meet

1 each other they cancel and the wave is said to be phase  
2 cancelled. A perfectly phase cancelled wave has no  
3 electromagnetic energy.

4

5 Both constructive and destructive interference of light  
6 can be demonstrated by a double split experiment  
7 whereby light from a single source falls on a screen  
8 containing two closely spaced slits. If a viewing  
9 screen is placed behind the first screen, a series of  
10 bright and dark lines will be seen on the viewing  
11 screen. This series of lines is called an interference  
12 pattern.

13

14 The bright lines of an interference pattern are areas  
15 of constructive interference, and the dark lines are  
16 areas of destructive interference. The pattern is  
17 generated as waves of a particular wavelength enter the  
18 two slits. The waves spread out in all directions  
19 after passing through the slits so as to interfere with  
20 each other. If a wave from each slit reaches the  
21 center of the viewing screen, and these waves travel  
22 the same distance before they hit the screen, they will  
23 be in phase and a bright spot indicating constructive  
24 interference will occur at the center of the viewing  
25 screen. There will also be constructive interference  
26 at each point the paths of two light rays differ by one  
27 wavelength or multiples of one wavelength. However, if  
28 one ray travels an extra distance of one-half a  
29 wavelength or some multiple of a half wavelength, the  
30 two waves will be exactly out of phase when they reach  
31 the screen, and so a dark band will appear in the  
32 interference pattern indicating destructive  
33 interference. Thus, you get a series of bright and  
34 dark lines in the interference pattern called  
35 "fringes".

36

1 The double slit experiment is one method of producing  
2 destructive interference. However, only a small  
3 portion of the source light is cancelled. Another  
4 method of producing destructive interference of light  
5 has been accomplished by using a beam splitter,  
6 mirrors and a laser. This type of device is often  
7 referred to as an interferometer.

8  
9 An interferometer works on the following principle. A  
10 laser is used in conjunction with a beam splitter to  
11 cause the laser beam to split in two, with a certain  
12 percentage of light taking one path and a certain  
13 percentage of light taking another path. The path of  
14 one of the split beams can be delayed by using amovable  
15 mirror such that the beam can be reflected back  
16 parallel with the unreflected beam by variable path  
17 lengths which can differ by fractions of a wavelength.  
18 The degree of cancellation depends on the "coherence  
19 length" of the laser and the narrowness of the  
20 chromatic line. For these reasons, a laser of  
21 extremely high quality is required to produce a  
22 significant degree of cancellation. However, no laser  
23 produces purely monochromatic light and a fringe is  
24 produced regardless of the degree of cancellation. In  
25 order to produce a perfectly phase-cancelled  
26 non-fringing collinear beam, destructive interference  
27 must occur over all incident wavelengths and phases of  
28 the entire bandwidth of the incident light source, all  
29 of the light rays emitted by the source must be  
30 parallel, each photon in the beam must be paired with  
31 another photon having the exact same wavelength, and  
32 the path lengths of half of the photons must be delayed  
33 by a multiple of exactly one half wavelength with  
34 respect to the path lengths of their paired photon  
35 partners.

1 No conventional arrangement can achieve this result.  
2 Although a pair of semi-silvered mirrors could be  
3 placed such that one specific wavelength could be made  
4 to interfere it cannot be correct for all wavelengths.  
5 A refractive element could be used to adjust the delay.  
6 However, as this only works for non-zero incident  
7 angles, the result would be that each wavelength would  
8 be travelling along non-parallel paths whose angle can  
9 only be increased by the mirrors so the beam could  
10 never form a collinear beam and so individual photons  
11 can never pair.

12  
13 Accordingly, it is an object of the invention to  
14 provide a highly efficient optical device which will  
15 produce an output beam which is non-fringing, collinear  
16 and phase cancelled such that: (a) destructive  
17 interference occurs for all incident wavelengths and  
18 phases over a bandwidth of at least 1 % plus or minus  
19 the center wavelength of a coherent light source such  
20 as a laser; (b) all of the output beam's light rays  
21 are parallel; (c) each photon in the output beam is  
22 paired with another photon having the exact same  
23 wavelength; and, (d) the path lengths of half of the  
24 photons are delayed by a multiple of exactly one half  
25 wavelength with respect to the path lengths of their  
26 paired photon partners.

## 27 28 SUMMARY OF THE INVENTION

29  
30 The invention achieves the above-described object and  
31 other objectives in the following way:

32  
33 An optical device is provided which consists of a  
34 holographic element ("hologram") and a refractive  
35 optical material of a specifically selected refractive  
36 index. The hologram is constructed with a diffraction

1 grating that will induce a wavelength-dependent angle  
2 of diffraction for an incident optical beam of a given  
3 entry angle. The assembly of the hologram and  
4 refractive optical material are such that the  
5 wavelength-dependent variation in refraction angle  
6 induced by the refractive material will be equal and  
7 opposite the wavelength-dependent variation in  
8 diffraction angle induced by the hologram such that the  
9 angles mutually cancel for each wavelength of the  
10 incident optical beam.

11  
12 In another embodiment, the previously described optical  
13 device is combined with a second hologram such that the  
14 optical device consists of two holograms and an  
15 intervening (refractive) optical material. Both  
16 holograms are constructed with similar diffraction  
17 gratings that will induce the same wavelength-dependent  
18 angle of diffraction for an incident optical beam of a  
19 given entry angle and both holograms are constructed  
20 with the same average refractive index. However, each  
21 hologram has a predetermined efficiency which is  
22 different from the efficiency of the other hologram.  
23 The first hologram is preferably about 50% efficient or  
24 half as efficient as the second hologram and the second  
25 hologram is preferably close to 100% efficient.

26  
27 The first hologram is positioned parallel to and  
28 spatially separated from the second hologram by an  
29 intervening optical material. The intervening optical  
30 material is essentially sandwiched by the two  
31 holograms. The intervening optical material has a  
32 specifically selected refractive index which is  
33 different from the average refractive indices of the  
34 holograms. The angle of refraction induced by the  
35 intervening optical material is also wavelength  
36 dependent.

1 By establishing a particular refractive index for the  
2 intervening optical material, a wavelength-dependent  
3 variation in refraction angle induced by the  
4 intervening optical material can be made equal and  
5 opposite to the wavelength-dependent variation in  
6 diffraction angle induced by the first hologram such  
7 that the angles mutually cancel for each wavelength of  
8 an incident optical beam having a given entry angle for  
9 the first hologram of the optical device.

10  
11 Because the first hologram is close to 50% efficient,  
12 approximately 50% of the incident optical beam will  
13 pass through the hologram undiffracted and  
14 approximately 50% of the beam will be diffracted such  
15 that two beams will be produced by the first hologram.  
16 Both beams will traverse the intervening optical  
17 material and impinge upon the second hologram at  
18 different angles. The diffracted beam will pass  
19 through the second hologram affected only by the change  
20 in refractive index whereas the undiffracted beam will  
21 interact with the diffraction grating of the second  
22 hologram and be diffracted at an angle such that both  
23 beams will exit the second hologram parallel to each  
24 other.

25  
26 By small adjustments of the second hologram, the two  
27 exit beams can be made to overlap and the originally  
28 undiffracted beam can be intercepted by the second  
29 hologram such that it takes a path some multiple of a  
30 half wavelength different from the path of the  
31 originally diffracted beam. The combined beam will be  
32 phase cancelled for all incident wavelengths and phases  
33 over a bandwidth of at least 1% plus or minus the  
34 center wavelength of the incident optical beam.

35  
36 Both the overall delay of the diffracted beam and the



1 overall efficiency of diffraction for the holograms can  
2 be adjusted by simply changing the angle of incidence  
3 on the first hologram. As the angle of incidence is  
4 changed, a greater or lesser percentage of the incident  
5 light can be cancelled. The fundamental difference  
6 between this effect and that of a simple fixed delay on  
7 one of the beams is that as the angle of the total  
8 element becomes aligned with the ideal, a greater  
9 percentage of the incident light will pass through the  
10 defined path. All of the light passing through the  
11 defined path will result in a perfect cancellation.  
12 So, whereas in a conventional interferometer a series  
13 of fringes will be seen, the output of the element as  
14 described in this invention will produce a single  
15 fringe or beam with a greater or lesser percentage of  
16 cancellation proportional to the amount of the incident  
17 beam allowed to take the prescribed path.

18  
19 Another aspect of the invention includes methods for  
20 producing the previously described optical device. In  
21 the production of the device, two lasers are used to  
22 generate a mixed beam of collinear light consisting  
23 essentially of two different wavelengths. The mixed  
24 beam is directed at one of the holograms at a given  
25 entry angle such that two diffracted beams exit the  
26 hologram at different angles and project onto a  
27 photo-sensor array a distance  $L$  from the exit side of  
28 the hologram. The distance between the projection  
29 points of the two diffracted beams is measured at the  
30 array.

31  
32 An intervening optical material having a long dimension  
33 equal to  $L$  and a selected initial refractive index is  
34 positioned between the photo-sensor array and a test  
35 photopolymer which has the same average refractive  
36 index as the hologram such that its long dimension is

1 perpendicular to the test photopolymer and the array.  
2 The same mixed beam is directed at the test  
3 photopolymer such that two exit beams are projected by  
4 the intervening optical material onto the array. The  
5 refractive index of the intervening optical material is  
6 then adjusted by polymerization. As the refractive  
7 index of the intervening optical material changes, the  
8 distance between the projection points of the refracted  
9 beams changes. The polymerisation of the intervening  
10 optical material is stopped at that point when the  
11 displacement between the projection points of the  
12 refracted beams measures the same as the displacement  
13 between the projection points of the diffracted beams.  
14  
15 The intervening optical material is then secured to the  
16 first hologram such that its short dimension is  
17 perpendicular to the hologram. A second hologram, twice  
18 as efficient as the first hologram, is positioned at  
19 the face of the intervening optical material opposite  
20 the first hologram. An incident optical beam having a  
21 suitable entry angle is directed at the first hologram  
22 so that two exit beams are produced by the second  
23 hologram. Slight rotational and lateral adjustments of  
24 the second hologram are made until the beams overlap  
25 and a position of maximum cancellation is achieved.  
26  
27 The optical device described above overcomes the  
28 limitations associated with interferometers in that it  
29 can produce a non-fringing phase-cancelled beam for all  
30 incident wavelengths and phases over a bandwidth of at  
31 least 1% plus or minus the center wavelength of a  
32 coherent light source such as a laser. Furthermore,  
33 the device disclosed herein represents a simple and  
34 reliable method for the creation of a phase-cancelled  
35 collinear beam even when the source laser is of  
36 relatively low quality and power and has a limited

1 coherence length. The production of such a device  
2 allows research into the properties of phase-cancelled  
3 collinear beams to be undertaken at moderate cost and  
4 is a basis for the generation of such beams for other  
5 scientific and commercial applications.

6  
7 Other objects, features and advantages of the invention  
8 will become apparent from a reading of the  
9 specification when taken in conjunction with the  
10 drawings.

#### 11 12 BRIEF DESCRIPTION OF THE DRAWINGS

13  
14 Fig. 1 is a diagrammatic cross-section of an  
15 overly simplified photopolymer hologram which is  
16 provided for the purpose of illustrating the potential  
17 interaction of light with the differing refractive  
18 indices of a photopolymer hologram as discussed in the  
19 background section of the following detailed  
20 description;

21  
22 Fig. 2 is a flow chart of a method of producing a  
23 device in accordance with the present invention;

24  
25 Fig. 3 is a schematic perspective view  
26 illustrating the method;

27  
28 Figs. 4A and 4B are diagrammatic plan views  
29 illustrating the method; and

30  
31 Fig. 5 is a diagrammatic cross-section  
32 illustrating a device in accordance with the invention.

#### 33 34 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

35  
36 For clarity, a brief background of lasers and holograms

1 and relevant terminology is provided.

2

3 The term "laser" is an acronym for Light Amplification  
4 by Stimulated Emission of Radiation. To generate a  
5 laser light source, a medium containing a distribution  
6 of similar atoms in a solid or gaseous transparent  
7 suspension is generally heated, or otherwise excited,  
8 to produce a majority of atoms at an excited state with  
9 electrons in high orbits outside the atom's "ground" or  
10 unexcited state. Introduction of a beam of light into  
11 the medium results in the absorption and re-emission of  
12 photons from the excited atoms. Because the atoms are  
13 at a threshold condition of excitation, the  
14 introduction of a photon causes the atom to absorb and  
15 re-emit the incident photon along with a second photon  
16 of the same wavelength and phase. This process tends to  
17 cause a "cascade" as each newly emitted photon  
18 stimulates other atoms to absorb and emit, thus  
19 amplifying the light. In an ideal world, the resulting  
20 light from such a system would be coherent so that all  
21 the light would be of the same phase and monochromatic  
22 in that it would consist of a single wavelength. In  
23 practice however, the atomic excitation is not perfect  
24 and several different energy states are stimulated  
25 among atoms in the suspension. This yields a narrow  
26 spectrum of light, often in a temporally spaced rhythm  
27 known as "mode hopping", as a majority of photons shift  
28 from one wavelength to the next. For various reasons  
29 the refractive index of the stimulated medium is often  
30 inconstant, and the thermal excitation tends to cause  
31 the phase to wander over time. The time period of such  
32 wandering divided into the speed of light defines the  
33 coherence length of a laser beam. This can vary  
34 between a few microns to many meters depending on laser  
35 type.

36

1 Holograms and their method of manufacture are well  
2 known in the art. A hologram is essentially a  
3 diffraction grating. A diffraction grating is created  
4 when the photopolymer is exposed to a reference beam of  
5 angle A and an incident beam of angle B. The  
6 diffraction grating, having been created by the passage  
7 of light at specific angles, tends to form as a  
8 mutually interactive three dimensional lattice which  
9 represents the desired fringe pattern only at a  
10 specific incident angle of the replay beam. Light  
11 entering the hologram with the same angle as the replay  
12 or reference beam will interact with the differential  
13 refractive indices of the diffraction grating and be  
14 diffracted at a new wavelength dependent angle. Any  
15 other angle will tend to miss the differential  
16 refractive indices of the diffraction grating and  
17 instead interact with the sum of the refractive indices  
18 of the hologram, as if in fact the hologram were all of  
19 a single average refractive index. Figure 1 shows the  
20 effect: note that paths a1 and a2 pass through more or  
21 less equal amounts of low (L) refractive index and high  
22 (H) refractive index, whereas at a certain critical  
23 angle, paths b1 and b2 pass through differential  
24 refractive indices.

25  
26 The efficiency of a photopolymer hologram is measured  
27 by comparing the incident and non-interacted light to  
28 the light that is transmitted by diffraction in the  
29 intended direction of the holographic optical element.  
30 The extent to which light is diffracted depends on how  
31 extensive the diffraction grating is present. The  
32 degree to which the diffraction grating is present is  
33 dependent on the extent to which polymerization and  
34 crosslinking of the holographic photopolymer is allowed  
35 to proceed. Polymerization and crosslinking of the  
36 photopolymer occurs when the photopolymer is exposed to

1 the light source used to create the diffraction grating  
2 and during subsequent exposure to ultraviolet light and  
3 thermal curing. By controlling the extent of  
4 polymerization and cross-linking, one can control the  
5 degree to which the diffraction grating is present and  
6 thus the efficiency of the hologram. The efficiency of  
7 holograms made from metal-based emulsions such as  
8 silver halide can be varied by varying the grain size  
9 of the emulsion.

10

11 The phenomenon of holographic efficiency is used in the  
12 described device to modify the percentage of light that  
13 is forced to take the phase cancelling path, since only  
14 the light which passes through the differential  
15 refractive indices will result in an interference  
16 pattern and thus result in a diffracted path. In  
17 practice the H and L portions of the hologram are less  
18 well defined due to incomplete polymerisation and so  
19 the efficiency is reduced even at the ideal angle as  
20 explained in the polymerisation discussion above.

21

22 Also fundamental to a full understanding of the  
23 invention is the phenomenon and properties of  
24 refraction. As a light ray passes through two optical  
25 mediums having different refractive indices and the  
26 light ray is at any angle other than perpendicular  
27 (normal) to the interface between the optical mediums,  
28 it will undergo a change of angle becoming more acute  
29 if the transition is from a lower to a higher index and  
30 more oblique if the transition is from a higher to a  
31 lower index. This phenomenon can be easily understood  
32 if it is remembered that the higher the refractive  
33 index of a medium the slower light travels through that  
34 medium. Thus, as a light ray enters a medium of  
35 higher refractive index at an angle, the light ray will  
36 be slowed down and thus bend toward the slowed side.

1 The angle of bend is dependent on the difference in the  
2 refractive indices of two optical mediums and the  
3 wavelength of the incident light beam.

4  
5 If a beam of light passes through an intervening  
6 optical material having a different refractive index  
7 compared to the refractive index of the medium the beam  
8 is travelling in (an example would be light passing  
9 through a window), the change in refractive index at  
10 the entry to and exit from the intervening optical  
11 material will be equal and opposite such that when the  
12 beam enters the intervening optical material the beam  
13 will bend one direction, and when the beam exits the  
14 intervening optical material the beam will be bent back  
15 in the opposite direction an equal amount so that the  
16 entry beam and exit beam will be parallel. However,  
17 the point at which the beam exits the intervening  
18 optical material will be shifted laterally compared to  
19 where the beam would have exited had the original entry  
20 beam passed straight through the intervening optical  
21 material unrefracted. The amount of lateral shift is  
22 dependent on the angular shift within the intervening  
23 optical material and the distance between the entry and  
24 exit.

25  
26 In this invention, the efficiency of a second hologram  
27 is set as close to 100 % as possible and the efficiency  
28 of a first hologram is set at half the efficiency of  
29 the second hologram, close to 50%. When a coherent beam  
30 of light of a given entry angle enters the first  
31 hologram, approximately 50% of the beam will pass  
32 through the first hologram affected only by the change  
33 in refractive index and approximately 50% of the beam  
34 will be diffracted. As both beams enter the  
35 intervening optical material they encounter another  
36 change in refractive index which induces a

1 wavelength-dependent change in angle for each beam. A  
2 refractive index for the intervening optical material  
3 is selected which induces a wavelength-dependent change  
4 in refraction angle that is equal and opposite the  
5 wavelength-dependent change in diffraction angle  
6 induced by the first hologram so that the angles  
7 mutually cancel for each wavelength of the diffracted  
8 beam. Thus, the angular path of the diffracted beam  
9 across the intervening optical material is essentially  
10 opposite its angular path of exit from the first  
11 hologram.

12  
13 When the diffracted beam exits the intervening optical  
14 material and enters the second hologram the change in  
15 refractive index is equal and opposite the change in  
16 refractive index which occurred as the diffracted beam  
17 left the first hologram and entered the intervening  
18 optical medium. This must be since the average  
19 refractive indices of the two holograms are the same.  
20 Thus, the diffracted beam will be refracted by the  
21 second hologram such that its angle of departure from  
22 the second hologram will be parallel to its angle of  
23 departure from the first hologram (the original angle  
24 of diffraction). Note that the diffracted beam would  
25 have an improper entry angle with respect to the  
26 diffraction grating of the second hologram and would  
27 pass through the second hologram affected only by the  
28 change in refractive index.

29  
30 The undiffracted beam which exits the first hologram  
31 passes through both the first hologram and interveni...  
32 optical material and into the second hologram affected  
33 only by the change in refractive index. Therefore, the  
34 undiffracted beam exits the intervening optical  
35 material and enters the diffraction grating of the  
36 second hologram by a path which is shifted laterally



1 but otherwise parallel with the path it had as it  
2 entered the first hologram. Thus, the undiffracted  
3 beam will have the correct entry angle to interact with  
4 the differential refractive indices of the diffraction  
5 grating of the second hologram. Because the second  
6 hologram is close to 100% efficient, nearly all of the  
7 undiffracted beam will be diffracted and thus exit the  
8 second hologram parallel to the originally diffracted  
9 beam.

10

11 By slight movements of the second hologram, the two  
12 exit beams can be made to overlap over a large portion  
13 of the diameter of their beams and the originally  
14 undiffracted beam can be intercepted by the second  
15 hologram such that it takes a path some multiple of a  
16 half wavelength different from the path taken by the  
17 originally diffracted beam. The resulting combined  
18 beam will be phase cancelled for all wavelengths and  
19 phases over a bandwidth of at least 1% plus or minus  
20 the source center wavelength of the incident optical  
21 beam.

22

23 The first and second holograms are constructed as will  
24 now be described. The sequence of operations is  
25 summarised in the flowchart of Fig. 2.

26

27 The diffraction grating of the first hologram is  
28 created by exposing a holographic plate or film to a  
29 reference beam of angle A and an incident beam of angle  
30 B. In the prototype invention, an argon ion laser is  
31 used as the light source, however, different lasers can  
32 be used relative to the characteristics of the  
33 holographic film one is using.

34

35 The laser is mounted on a laboratory optical bench and  
36 a beamsplitter and mirrors are used to cause the laser

1 beam to split and project upon the holographic plate as  
2 a reference beam and incident beam having the correct  
3 angles. In the case of the prototype, the reference  
4 beam angle was approximately 30 degrees from  
5 perpendicular to the hologram and the incident beam  
6 angle was approximately 2-3 degrees from  
7 perpendicular. These angles can be varied as long as  
8 neither beam is exactly perpendicular to the hologram  
9 or so close to horizontal with the plane of the  
10 hologram that the beams cannot interact with the  
11 hologram to form a diffraction grating.

12  
13 The efficiency of the first hologram is set close to  
14 50% preferably by controlling the exposure of the  
15 photopolymer to limit the polymerisation by that amount  
16 or in the case of a silver halide hologram by reducing  
17 the contrast to half of that achievable. By measuring  
18 the difference in intensity between the output beams  
19 and the input beams with a photo sensor, one can  
20 determine the point at which the desired efficiency is  
21 achieved. The second hologram is manufactured using  
22 the same reference and incident beam at the same angles  
23 but with an efficiency as near 100% as is practical or  
24 to the limit achievable with a silver halide hologram.  
25 Modern photopolymers typically allow an efficiency of  
26 up to 97% once a series of iterative exposure tests and  
27 thermal curing tests have been completed. Experience  
28 shows that a consistent exposure and bake for a  
29 particular photopolymer from a particular manufacturers  
30 batch can be determined after a few iterations for any  
31 chosen polymerisation efficiency and therefore for any  
32 chosen holographic diffraction efficiency.

33  
34 Since the consistency of the manufacture of  
35 photopolymers is not yet ideal the calculation of  
36 resultant diffraction and refraction ratios of the

1     hologram is impossible thus pre-determination of a  
2     specific refractive index for the intervening optical  
3     material is currently impossible. The solution to the  
4     problem is to exploit the thermal curing properties of  
5     photopolymers as described below.

6  
7     Referring to Fig 3 and Fig 4A, a pair of lasers with a  
8     wavelength difference of a few nanometers are set up to  
9     provide beams 10 and 12 to a beam splitter 14, and thus  
10    to produce a single collinear mixed beam 16 through an  
11    oven (not shown) and thence to project at a screen or,  
12    preferably, at a sensor array 18. The hologram 2  
13    which is 100% efficient is placed in the path of the  
14    beam 16 at point X such that the beam 16 impinges on  
15    the hologram 2 at the reference angle  $\alpha$ . Since the  
16    incident beam 16 is essentially composed of two  
17    different wavelengths of light and the angle of  
18    diffraction for a given hologram is wavelength  
19    dependent, two exit beams (20 and 22) will be produced  
20    by the hologram 2. The wavelength of light in one beam  
21    will be shorter than the wavelength of light in the  
22    other beam and both beams will be projected on the  
23    sensor array 18 as two projection points 24 and 26.  
24    The difference between the centers of the two  
25    projection points 24 and 26 is measured by the  
26    photosensor array at point Y and recorded.

27  
28    The hologram 2 is removed and replaced at X with a test  
29    photopolymer 28 (Fig. 4B) which has been exposed to the  
30    same total energy in Joules of incoherent light as the  
31    hologram 1 has been exposed to coherent light, such  
32    that the average refractive index of the test  
33    photopolymer 28 equals the average refractive index of  
34    the hologram 1. An intervening optical material in the  
35    form of an uncured photopolymer 30 is placed between  
36    the test photopolymer 28 and the sensor array 18. The

1 differential between the refractive index of the  
2 hologram 2 or test photopolymer 28 and the refractive  
3 index of the intervening optical material 30 will  
4 define the angle of refraction for a given wavelength  
5 at the interface between the first hologram 1 and the  
6 intervening optical material 30 (interface 32 in Fig.  
7 5), and it is this angle's dependence on wavelength that  
8 this set up is designed to define.

9  
10 The refractive index of the intervening optical  
11 material 30 is determined by the structure and density  
12 of the photopolymer which is used as to make the  
13 intervening optical material 30. The structure and  
14 density of this photopolymer can be varied depending on  
15 the amount of light to which the photopolymer and its  
16 activating dye is exposed to and also to the subsequent  
17 crosslinking induced by exposure to an elevated  
18 temperature. By exposing the photopolymer to a  
19 suitable amount of light and then monitoring the  
20 refractive index during elevated temperature curing  
21 (cross linking), a specific refractive index can be  
22 achieved.

23  
24 The actual refractive index will change slowly  
25 proportional to the time and temperature. It can be  
26 frozen at a specific value by dropping the temperature  
27 below a critical temperature at which cross linking  
28 occurs for a given photopolymer. The process is made  
29 difficult by the fact that the refractive index changes  
30 in only one direction and by the fact that the curing  
31 process can not be instantaneously stopped. However,  
32 one can experiment with a sample of the same  
33 photopolymer and by carefully observing the change in  
34 angle after the temperature is dropped below the curing  
35 point, one can easily see by how much in advance of the  
36 desired angle the curing temperature must be reduced to

1 the critical temperature. The critical temperature of  
2 the photopolymer will represent the maximum operating  
3 temperature of the finished element since further  
4 exposure to elevated temperatures will cause the  
5 refractive index to change from the desired refractive  
6 index previously established by the above-described  
7 process of polymerization and cross-linking.

8  
9 Almost any photopolymer of sufficient range of  
10 refractive index may be used to make the intervening  
11 optical material, including the same photopolymer used  
12 for the production of the holograms. All that is  
13 required of it is that it can be cured to a mean  
14 refractive index that is different from the average  
15 refractive index of the holograms and that it is  
16 homotropic in that the speed of light in this material  
17 is the same in all directions. Low cost photopolymers  
18 such as the ultraviolet curing cements made by the  
19 Loktite Corporation have been used for this purpose.  
20 Generic dye activated photopolymer is also a suitable  
21 material and is available from several sources. The  
22 formulation can be determined from various published  
23 papers on the subject.

24  
25 The initial refractive index of the photopolymer which  
26 is to be used for the intervening optical material 30  
27 is made higher or lower than the average refractive  
28 index of the hologram 1 depending on the change of  
29 refractive index which is necessary to bend the  
30 diffracted exit beam in the desired direction. All  
31 that is important is that an initial refractive index  
32 is chosen for the intervening optical material 30 such  
33 that the change of refraction between the first  
34 hologram 1 and the intervening optical material 30 will  
35 cause the exit beam from the hologram 1 to bend back  
36 opposite its path of deflection as it passes through

1 the intervening optical material. Since the  
2 diffraction angle for the hologram 1 is known, a  
3 photopolymer can be chosen having the necessarily  
4 higher or lower initial refractive index. The  
5 photopolymer to be used for the intervening optical  
6 material 30 has typically been treated with sufficient  
7 ultraviolet light that the photopolymer is converted to  
8 a solid having an initial refractive index as  
9 previously described.

10

11 The manufacture of the intervening optical material 30  
12 is as follows:

13

14 Referring again to Figs. 3 and 4, the hologram 2 at  
15 position X is removed and replaced with the test  
16 photopolymer 28. A photopolymer which is to be used  
17 for the intervening optical material 30 is prepared so  
18 as to have a long dimension L and a narrow dimension M.  
19 Dimension L is made equal to the distance X-Y in Figs.  
20 3 and 4. Distance X-Y equals the distance between the  
21 test photopolymer 28 and the sensor array 18 and is the  
22 same as the distance between the hologram 1 and the  
23 sensor array 18. In the prototype, a photopolymer 6 cm  
24 long and 0.3 mm wide has been used to make the  
25 intervening optical material 30. However, as will be  
26 explained later, handling and construction  
27 considerations are the main criteria for the actual  
28 size of dimensions M and L.

29

30 One end of photopolymer 30 is placed in contact with  
31 the sensor array and the other end is placed against  
32 the test photopolymer 28 at point X (Fig. 4B) so that  
33 dimension L of photopolymer 30 is perpendicular to the  
34 sensor array 18.

35

36 When the pair of lasers are energized, a collinear beam

1 16 is projected into the oven through the test  
2 photopolymer 28 and photopolymer 30. At the exit side  
3 of photopolymer 30 the shorter wavelengths of the two  
4 lasers will be laterally displaced relative to the  
5 longer wavelengths such that two beams 20 and 22 will  
6 exit photopolymer 30 and impinge on the sensor array 18  
7 as two projection points 24 and 26 (Fig. 4B). By  
8 placing photopolymer 30 with its greater dimension L  
9 perpendicular to the array 18, a more easily measured  
10 displacement of the projection points of the two beams  
11 can be made at Y than would be the case if dimension XY  
12 were to be made equal to dimension M which would be the  
13 operational dimension of photopolymer 30.  
14

15 Initially, ultraviolet light is used to cure  
16 photopolymer 30. As photopolymer 30 cures, the  
17 progressive change in the difference between the  
18 centers of the projection points 24, 26 of the two  
19 beams 20 and 22 can be measured at the sensor array 18.  
20 Initially, the projection points 24, 26 will be close  
21 together. As the curing process starts, the projection  
22 points 24, 26 will begin to spread. As the distance  
23 between the projection points 24, 26 begins to approach  
24 the desired spread, the ultraviolet light is turned off  
25 and the oven, which has been set to the photopolymer  
26 manufacturer's recommended curing temperature, is  
27 turned off. As previously mentioned, the curing  
28 process cannot be instantaneously stopped. Therefore,  
29 the oven is turned off far enough in advance such that  
30 when the curing process finally stops, the centers of  
31 the projection points 24, 26 will measure exactly the  
32 same distance as that measured between the centers of  
33 the projection points produced by the first hologram 1  
34 thus establishing the refractive index of photopolymer  
35 30.  
36

1 At this point, the linear shift of the projection  
2 points 24, 26 of the two beams 20, 22 which were  
3 angularly shifted due to the change of refractive index  
4 between the test photopolymer 28 and photopolymer 30 is  
5 made equal to the linear shift caused by the equal but  
6 opposite angular shift of the beams 20, 22 which were  
7 diffracted by the hologram 1 as previously measured.  
8 Thus, in the finished optical device, the change in  
9 refractive index between the first hologram 1 and the  
10 intervening optical material 30 will be such that the  
11 wavelength-dependent variation in refraction angle  
12 induced by the refractive material 30 will be equal and  
13 opposite the wavelength-dependent variation in  
14 diffraction angle induced by the first hologram 1 such  
15 that the angles mutually cancel for each wavelength of  
16 the incident optical beam.

17

18 The assembly of Fig 5 can now be made.

19

20 The intervening optical material (photopolymer 30) is  
21 inserted with dimension M between the two holograms 1  
22 and 2. The hologram 1 which is 50% efficient is  
23 stabilized in its alignment with respect to the  
24 intervening optical material. A laser beam B having  
25 the correct entry angle to interact with the  
26 differential refractive indices of the diffraction  
27 grating of the hologram is directed at the stabilized  
28 hologram 1 so two output beams, p1 and p2 of Fig. 5,  
29 are produced by the optical device. Reference 34  
30 indicates holographic deflection. Both beams exit the  
31 intervening optical material 30 at different angles.  
32 Beam p1 represents the diffracted beam.

33

34 A small dab of UV curing cement is applied to either  
35 the exposed face of the intervening optical material 30  
36 or the second hologram 2. As the second hologram 2 is



1 pushed up against the intervening optical material 30,  
2 it is pivoted about the axis of the exiting beams until  
3 beams p1 and p2 line up as a single spot on a target  
4 such as a frosted glass or a CCD. Then, the second  
5 hologram 2 is adjusted laterally. As the second  
6 hologram 2 is moved laterally (perpendicular to  
7 dimension M), the beam will be seen to modulate between  
8 light and dark. Upon closer examination of the spot,  
9 the two beams p1 and p2 can be seen overlapping as two  
10 circles on the target. This can be facilitated by  
11 magnifying the beam projection point with a lens  
12 (taking the usual precautions for eye protection) or  
13 connecting the CCD to a monitor.

14  
15 The desired condition is to achieve both maximum  
16 overlap of the beams p1 and p2 and maximum cancellation  
17 simultaneously. Beam p2 which is diffracted by the  
18 second hologram 2 tends to have a slightly harder edge  
19 than beam p1. This makes aligning the overlap easier  
20 since, in practice, beam p1 will form a slight halo or  
21 "corona" around beam p2 making it easy to see when the  
22 beams are ideally aligned and maximum cancellation  
23 (destructive interference) has been achieved. This  
24 adjustment is possible because the diameters of the  
25 beams are large with respect to the wavelength and by  
26 adjusting the hologram laterally, that portion of beam  
27 p2 taking a path some multiple of a half wavelength  
28 longer than the beam p1 can be intercepted. The  
29 differential required between the two beam paths occurs  
30 many times within the diameter of the combined beams so  
31 the second hologram can be adjusted over several  
32 destructive peaks until the best position is chosen.

33  
34 Once the operator is satisfied that the optimum  
35 condition is achieved, the device as a whole is exposed  
36 to ultraviolet to cure the cement. Various

1 manufacturers make such cement and the ideal curing  
2 exposure will be as recommended by the manufacturer of  
3 the cement used.

4  
5 The difference between several peak cancellations in  
6 terms of beam overlap is small and so the overall  
7 performance of the device will only vary a few  
8 fractions of a percent from optimum even if the device  
9 is quite grossly misaligned in terms of beam overlap.  
10 Also, even if the cancellation point is not perfect, a  
11 small adjustment in the entry angle of the replay beam  
12 will correct it to some extent. For maximum  
13 efficiency, the positioning of the second hologram 2  
14 should be performed carefully. For example, if the  
15 device is to be used as the aperture for a spatial  
16 filter in a powerful laser system, it is naturally  
17 important to insure that as little power as possible  
18 either bypasses the arrangement or is absorbed by it.

19  
20 The adjustment of the second hologram 2 can be  
21 accomplished by a micromanipulator such as would be  
22 used for the adjustment of a microscope stage. An  
23 alternative method is to use a piezoelectric transducer  
24 as a component of a suitably constructed jig. A  
25 piezoelectric transducer changes dimension proportional  
26 to an electric field. The holograms 1 and 2 and  
27 intervening optical material 30 can be held permanently  
28 in place by a clamp as an alternative to UV curing  
29 cement.

30  
31 Because of the relationship between the holograms 1 and  
32 2 and the intervening optical material 30 it is now  
33 possible to vary the incident wavelength by up to 2%  
34 while still maintaining perfect temporal cancellation  
35 of the beam. Actual intensity cancellation is less  
36 than perfect since the holographic polymerisation or

1 halide contrast efficiencies are never perfect.

2

3 The ability of the device to cancel a wide bandwidth of  
4 incident light is explained below with reference to Fig  
5 5. .

6

7 The wavelength of the incident light changes dimension  
8  $dx$  such that the longer the wavelength the greater  $dx$ .  
9 Thus the path length of  $p_1$  and the path length of  $p_2$   
10 will be wavelength dependent. By defining the mean  
11 value of  $dx$  it is possible to set the difference  
12 between path  $p_1$  and path  $p_2$  as an integer multiple of a  
13 half wavelength for the mean wavelength of the laser.  
14 If that multiple is odd, i.e. 1,3,5,7 etc., then the  
15 beams of  $p_1$  and  $p_2$  will cancel. Further, since the  
16 differential of  $p_1$  and  $p_2$  is defined by  $dx$  which is  
17 wavelength dependent, it can be seen that the delay of  
18  $p_2$  can be set to consistently equal one half wavelength  
19 over any wavelength that is interacting with the  
20 optical device and within a range such that  $dx$  does not  
21 exceed the diameter of the beams  $p_1$  and  $p_2$ . Defining  
22 the mean value of  $dx$  and setting the difference between  
23 path  $p_1$  and path  $p_2$  as an integer multiple of a half  
24 wavelength for the mean wavelength of the laser is  
25 accomplished simply by making small adjustments of the  
26 second hologram 2 as previously described. As the  
27 correct positioning of the second hologram 2 is  
28 established, the individual delay for each wavelength  
29 is made proportional to its wavelength.

30

31 Dimension  $M$  is important only as to how it relates to  
32  $dx$  and so defines the mean differential path length of  
33  $p_1$  to  $p_2$ . Since  $dx$  is freely adjustable, handling and  
34 construction considerations are the main criteria for  
35 the actual size of dimension  $M$ . As stated before,  
36 dimension  $L$  which is defined by the distance  $XY$ , is

1 chosen simply to ensure that the projection points can  
2 be sufficiently discriminated by the photosensor array  
3 18. Dimensions M and L are therefore only so labelled  
4 as to facilitate the description of the device. For  
5 example, successful devices have been constructed with  
6 dimension M as small as 0.05mm and as large as 1mm.  
7 The CCD photosensor array used in the prototype's  
8 construction was of sufficient resolution to allow  
9 dimension L to be less than 10mm, and in practice any  
10 commercial camera-type CCD array can be used at this  
11 dimension of L.

12  
13 Note that the lateral displacement of the replay beam  
14 is very small with respect to beam diameter. The  
15 interaction of the two beams from the second hologram 2  
16 is constant in terms of wavelength displacement through  
17 a wavelength variation of several percent. As the  
18 angle of the replay beam is changed, the interaction of  
19 the beam with the holograms changes. As the angle  
20 increases, more light passes through the grating  
21 without interacting. This is so because the  
22 differential refractive indices that define the grating  
23 are blurred by the passage of light through more than  
24 one index of the film, as is crudely represented in Fig  
25 1. Since the index is defined by the actual atomic  
26 density averaged through the path of a ray, this  
27 density varies over a very small scale. The result of  
28 this is that the probability of the cancellation of the  
29 beam changes from an absolute maximum defined by the  
30 peak efficiency of the hologram to a minimum of near  
31 random distribution. The output beam in the  
32 non-cancelled condition remains polarized but is  
33 reduced in coherence from the initial laser incident  
34 beam. The loss of coherence is unlikely to be a  
35 problem except in applications where a long range  
36 projection of over two million wavelengths is needed.

1     Within one million wavelengths, focusing can be  
2     achieved within a reasonable approximation of the  
3     diffraction limit.

4  
5     Note also that as the initial hologram passes a wave  
6     through the diffraction path or the non-diffraction  
7     path (depending only on the random chance of a specific  
8     photon passing through a polymerised portion of the  
9     hologram), a considerable portion of the delayed beam  
10    might be expected to consist of photons that would lack  
11    coherent partners taking the alternative path. In  
12    practice, the so called quantum entanglement of photons  
13    emitted from a laser source extends over a far greater  
14    volume of any laser source than had been previously  
15    thought. This results in the unexpected tendency of  
16    the photons passing through the device to self select  
17    into pairs, one taking the delayed path and one the  
18    short path. Without this effect the expected level of  
19    cancellation in the described device would be of the  
20    order of 70%. The actual cancellation measured is  
21    often greater than 98%.

22  
23    That the effect is truly cancellation rather than some  
24    form of absorption is readily determined by measuring  
25    the temperature of an element used to intercept a laser  
26    beam of known power. If the reduction of the beam  
27    intensity were due to absorption, then the temperature  
28    of the element would rise proportionately to the energy  
29    intercepted whereas in the case of cancellation, no  
30    temperature rise would be expected. Careful  
31    measurements show that no such temperature rise occurs,  
32    indicating that the 98% reduction in the beam intensity  
33    is indeed due to cancellation alone.

34  
35    Given the photon entanglement noted above, a practical  
36    maximum cancellation for room temperature experiments

1 has been found to be approximately 98%. This may be  
2 improved in controlled temperature applications and may  
3 be reduced if the environmental temperature must vary  
4 by more than ten degrees Celsius. The apparatus is  
5 capable of remaining stable at power densities of  
6 greater than 500 mW proving that the observed effect is  
7 true collinear cancellation (If the effect was caused  
8 by some misunderstood absorption phenomenon, the power  
9 would be absorbed and the element would melt as  
10 explained above).

11  
12 The optical device as herein described serves a purely  
13 practical application as an attenuator for high powered  
14 lasers. Simply putting a shutter across a high powered  
15 laser beam is not possible since the beam simply burns  
16 through. The above device can intercept a laser beam  
17 of any power and reduce its intensity by 98% without  
18 itself absorbing any energy. A practical experiment  
19 with a beam of 500mW has been conducted. The power  
20 density of the beam being  $312 \text{ W/cm}^2$ , the change in  
21 temperature was equivalent to only 0.1 percent of the  
22 incident power.

23  
24 Another simple application of the optical device would  
25 be the production of a spatial filter. A conventional  
26 spatial filter consists of a pin hole through which a  
27 laser is projected. Since the circumference of the  
28 hole is subject to the full power of the laser beam,  
29 the hole tends to burn away in a short time. To  
30 overcome this problem, an optical device in accordance  
31 with the above-described invention, could be made for  
32 the particular laser and then a pinhole drilled through  
33 it. When the laser beam is directed at the pinhole,  
34 rather than absorbing the radiation at the edge of the  
35 hole as in a conventional pinhole, all the light that  
36 failed to pass through the pinhole would simply be

1     cancelled.

2

3     This optical device also makes possible the  
4     construction of an achromatic optical lens whereby the  
5     lens would comprise the holographic diffraction  
6     gratings and refractive elements interrelated in the  
7     manner disclosed in the specification. In practice, a  
8     single holographic/refractive lens could not cover the  
9     entire optical spectrum. However, a group of such  
10    devices could cover the entire optical spectrum.

11   Although the use of photopolymers as described above is  
12   the presently preferred method of implementing the  
13   invention, this may be done in other ways.

14   Photographic type metal-based emulsions, such as silver  
15   halide may be used to construct the holograms.

16   However, the efficiency of an optical device utilizing  
17   silver halide holograms would be greatly reduced and a  
18   much more powerful laser would be needed to achieve as  
19   good a result as would be realized utilizing  
20   photopolymer holograms and a low powered laser. An  
21   emulsion may be used in conjunction with a photopolymer  
22   to set the holographic efficiencies by controlling the  
23   emulsion grain size. Alternatively, the holographic  
24   elements may be formed by photo exposure of emulsion  
25   layers, or by pressed elements produced from  
26   photographic masters.

27

28   The invention has been described hereinabove with  
29   reference to the use of a pair of holographic  
30   diffraction gratings. It would in principle be  
31   possible to achieve the benefits of the invention by  
32   using different forms of diffraction grating (or other  
33   optically dispersive elements) separated by an  
34   intermediate member of a chosen refractive index.

35

36   Further modifications may be made to the foregoing

1      embodiments within the scope of the present invention.



1

## 2 CLAIMS

3

4 1. An optical device comprising a first and a second  
5 hologram, each hologram having the same diffraction  
6 grating such that both holograms induce the same  
7 wavelength-dependent angle of diffraction and each  
8 hologram having the same average refractive index, said  
9 second hologram positioned parallel to the first  
10 hologram and spaced apart from the first hologram by an  
11 intervening optical material of a chosen refractive  
12 index, the refractive index of the intervening optical  
13 material being such that a wavelength-dependent angle  
14 of refraction induced by the intervening optical  
15 material at the interface between the first hologram  
16 and the intervening optical material is made equal and  
17 opposite to the wavelength-dependent diffraction angle  
18 induced by the first hologram such that the two angles  
19 cancel for any given wavelength of light.

20

21 2. A device according to claim 1, in which the first  
22 and second holograms have pre-determined efficiencies.

23

24 3. A device according to claim 2, in which the first  
25 hologram is about half as efficient as the second  
26 hologram.

27

28 4. A device according to claim 3, in which the first  
29 hologram has an efficiency of about 50% and the second  
30 hologram has an efficiency greater than 95%.

31

32 5. An optical device comprising a first and a second  
33 hologram and an intervening optical material of a  
34 chosen refractive index, each hologram having the same  
35 diffraction grating such that both holograms induce the  
36 same wavelength-dependent angle of diffraction and each

1     hologram having the same average refractive index,  
2     said first hologram having an efficiency half the  
3     efficiency of said second hologram, said second  
4     hologram positioned parallel to the first hologram and  
5     spaced apart from the first hologram by said  
6     intervening optical material, the arrangement being  
7     such that when an incident optical beam having a narrow  
8     spread of wavelengths around a center wavelength enters  
9     the first hologram at a given angle, the beam is split  
10    into two beams which traverse the intervening optical  
11    medium, enter the second hologram at different angles,  
12    and exit the second hologram by collinear paths which  
13    differ by some multiple of one half wavelength for all  
14    incident wavelengths and phases over a bandwidth of at  
15    least 1 % plus or minus the center wavelength of said  
16    incident optical beam.

17

18    6. A device according to claim 5, in which the first  
19    hologram has an efficiency of about 50% and the second  
20    hologram has an efficiency greater than 95%.

21

22    7. An optical apparatus comprising an optical device  
23    in accordance with any preceding claim, and a laser for  
24    directing an incident optical beam on said device.

25

26    8. An apparatus according to claim 7, in which the  
27    optical device is mounted rotatably with respect to the  
28    incident beam for variation of the angle of the  
29    incident optical beam with respect to the plane of  
30    refraction and diffraction of the optical device.

31

32    9. A method of producing an optical device in  
33    accordance with claim 5, the method comprising the  
34    steps of :

35

36       a) providing a first and a second hologram, each  
   hologram having the same diffraction grating such that

- 1 both holograms induce the same wavelength-dependent
- 2 angle of diffraction and each hologram having the same
- 3 average refractive index, said first hologram having an
- 4 efficiency half the efficiency of said second hologram;
- 5 b) positioning one of said holograms in the path of
- 6 a mixed beam of collinear light consisting essentially
- 7 of two different wavelengths such that two diffracted
- 8 beams exit the hologram at different angles to project
- 9 onto a photo-sensor array some distance L from the exit
- 10 side of the hologram;
- 11 c) measuring the distance between the projection
- 12 points of the two diffracted beams;
- 13 d) providing a first photopolymer having a chosen
- 14 initial refractive index and a long dimension equal to
- 15 L;
- 16 e) providing a second photopolymer having the same
- 17 average refractive index as said holograms;
- 18 f) substituting the second photopolymer at the
- 19 position of the hologram with respect to said mixed
- 20 beam;
- 21 g) positioning said first photopolymer between the
- 22 photo-sensor array and the second photopolymer so its
- 23 long dimension L is perpendicular to the array;
- 24 h) activating said mixed beam so that two refracted
- 25 beams project from said first photopolymer onto said
- 26 array;
- 27 i) adjusting the refractive index of the first
- 28 photopolymer by polymerization such that the distance
- 29 between the projection points of the refracted beams
- 30 changes;
- 31 j) stopping polymerisation at that point where the
- 32 displacement between the projection points of the
- 33 refracted beams measures the same as the displacement
- 34 measured between the projection points of the
- 35 diffracted beams;
- 36 k) removing said second photopolymer and securing it

1 to said first hologram;

2 1) positioning said second hologram at the face of  
3 the first photopolymer opposite the first hologram;

4 m) directing an incident optical beam having a  
5 narrow spread of wavelengths around a center wavelength  
6 at said first hologram such that two exit beams are  
7 produced by said second hologram;

8 n) adjusting said second hologram until the exit  
9 beams maximally overlap and a position of maximum  
10 cancellation is achieved; and

11 o) securing said second hologram to the first  
12 photopolymer at said adjusted position.

13

14 10. A method of using an optical device to produce a  
15 continuously cancelled collinear beam for all incident  
16 wavelengths and phases over a bandwidth of at least 1 %  
17 plus or minus the source center wavelength of an  
18 incident optical beam, said method comprising the  
19 following steps:

20 a) providing an optical apparatus in accordance with  
21 claim 7;

22 b) energizing said laser and directing the laser  
23 output beam to impinge on said optical device;

24 c) positioning said optical device to vary the angle  
25 of the incident beam with respect to the plane of  
26 refraction and diffraction of the optical device until  
27 a position of maximum cancellation is achieved.

28

29 11. A method of producing a continuously cancelled  
30 collinear beam for all incident wavelengths and phases  
31 over a bandwidth of at least 1 % plus or minus the  
32 source center wavelength of an incident optical beam,  
33 said method consisting of the steps of:

34 a) providing a first and a second hologram, each  
35 hologram having the same diffraction grating such that  
36 both holograms induce the same wavelength-dependent

- 1 angle of diffraction and each hologram having the same
- 2 average refractive index, said first hologram having an
- 3 efficiency half the efficiency of said second hologram;
- 4 b) positioning one of said holograms in the path of
- 5 a mixed beam of collinear light consisting essentially
- 6 of two different wavelengths such that two diffracted
- 7 beams exit the hologram at different angles to project
- 8 onto a photo-sensor array some distance  $L$  from the exit
- 9 side of the hologram;
- 10 c) measuring the distance between the projection
- 11 points of the two diffracted beams;
- 12 d) providing a first photopolymer having a chosen
- 13 initial refractive index and a long dimension equal to
- 14  $L$ ;
- 15 e) providing a second photopolymer having the same
- 16 average refractive index as said holograms;
- 17 f) substituting the second photopolymer at the
- 18 position of the hologram with respect to said mixed
- 19 beam;
- 20 g) positioning said first photopolymer between the
- 21 photo-sensor array and the second photopolymer so its
- 22 long dimension  $L$  is perpendicular to the array;
- 23 h) activating said mixed beam so that two refracted
- 24 beams project from said first photopolymer onto said
- 25 array;
- 26 i) adjusting the refractive index of the first
- 27 photopolymer by polymerization such that the distance
- 28 between the projection points of the refracted beams
- 29 changes;
- 30 j) stopping polymerisation at that point where the
- 31 displacement between the projection points of the
- 32 refracted beams measures the same as the displacement
- 33 measured between the projection points of the
- 34 diffracted beams;
- 35 k) removing said second photopolymer and securing it
- 36 to said first hologram;

- 1        l) positioning said second hologram at the face of
- 2        the first photopolymer opposite the first hologram;
- 3        m) directing a incident optical beam having a
- 4        narrow spread of wavelengths around a center wavelength
- 5        at said first hologram such that two exit beams are
- 6        produced by said second hologram;
- 7        n) adjusting said second hologram until the exit
- 8        beams maximally overlap and a position of maximum
- 9        cancellation is achieved; and
- 10       o) securing said second hologram to the first
- 11       photopolymer at said adjusted position.

12

13       12. An optical device which produces a phase cancelled  
14       collinear beam for all incident wavelengths over a  
15       bandwidth of at least 1% plus or minus the center  
16       wavelength of an incident optical beam when said  
17       optical beam has a narrow spread of wavelengths around  
18       a center wavelength and a given angle of entry to said  
19       device.

20

21       13. A spatial filter consisting of an optical device  
22       according to claim 5, said optical device having a hole  
23       of the desired circumference formed through it such  
24       that incident light that failed to pass through the  
25       hole would simply be cancelled.

26

27       14. An optical device comprising a hologram and a  
28       refractive optical material having a chosen refractive  
29       index, said hologram constructed with a diffraction  
30       grating that will induce a wavelength-dependent angle  
31       of diffraction for an incident optical beam of a given  
32       entry angle, the assembly of the hologram and  
33       refractive optical material being such that the  
34       wavelength-dependent variation in refraction angle  
35       induced by the refractive material will be equal and  
36       opposite the wavelength-dependent variation in

1 diffraction angle induced by the hologram such that the  
2 angles mutually cancel for each wavelength of the  
3 incident optical beam.  
4

5 15. An achromatic lens comprising a first and second  
6 hologram and an intervening optical material of a  
7 chosen refractive index, each hologram having the same  
8 diffraction grating such that both holograms induce the  
9 same wavelength-dependent angle of diffraction and each  
10 hologram having the same average refractive index,  
11 said first hologram having an efficiency half the  
12 efficiency of said second hologram, said second  
13 hologram positioned parallel to the first hologram and  
14 spaced apart from the first hologram by said  
15 intervening optical material, the arrangement being  
16 such that when an incident optical beam having a narrow  
17 spread of wavelengths around a center wavelength enters  
18 the first hologram at a given angle, the beam is split  
19 into two beams which traverse the intervening optical  
20 medium, enter the second hologram at different angles,  
21 and exit the second hologram by collinear paths which  
22 differ by some multiple of one half wavelength for all  
23 incident wavelengths and phases over a bandwidth of at  
24 least 1 % plus or minus the center wavelength of said  
25 incident optical beam.  
26

27 16. A method of producing an optical device in  
28 accordance with claim 5, the method comprising the  
29 steps of:

- 30 a) providing a first and a second hologram, each  
31 hologram having the same diffraction grating such that  
32 both holograms induce the same wavelength-dependent  
33 angle of diffraction and each hologram having the same  
34 average refractive index, said first hologram having an  
35 efficiency half the efficiency of said second hologram;  
36 b) providing an intervening optical material of a

1 chosen refractive index, the refractive index of the  
2 intervening optical material being such that a  
3 wavelength-dependent angle of refraction induced by the  
4 intervening optical material is equal and opposite to  
5 the wavelength-dependent diffraction angle induced by  
6 the holograms such that the two angles cancel for any  
7 given wavelength of light; and

8 c) securing the holograms to opposite sides of said  
9 intervening optical material such that the optical  
10 device produces a phase cancelled collinear beam for  
11 all incident wavelengths over a bandwidth of at least  
12 1% plus or minus the center wavelength of an incident  
13 optical beam when said optical beam has a narrow spread  
14 of wavelengths around a center wavelength and a given  
15 angle of entry to said device.

16

17 17. An apparatus according to claim 8 in which the  
18 degree of cancellation of the incident optical beam can  
19 be varied by rotating said optical device with respect  
20 to the incident optical beam such that the angle of  
21 incidence is changed and an exit beam is produced  
22 having a selected percentage of cancellation.

23

24 18. An optical device comprising a first wavelength  
25 dispersive element, a second wavelength dispersive  
26 element parallel to and spaced from the first  
27 wavelength dispersive element, and an intermediate  
28 member of a chosen refractive index, the arrangement  
29 being such that the angle of refraction at the entry to  
30 and exit from the intermediate member is equal to the  
31 frequency dependent change of angle introduced by the  
32 wavelength dispersive elements.

33

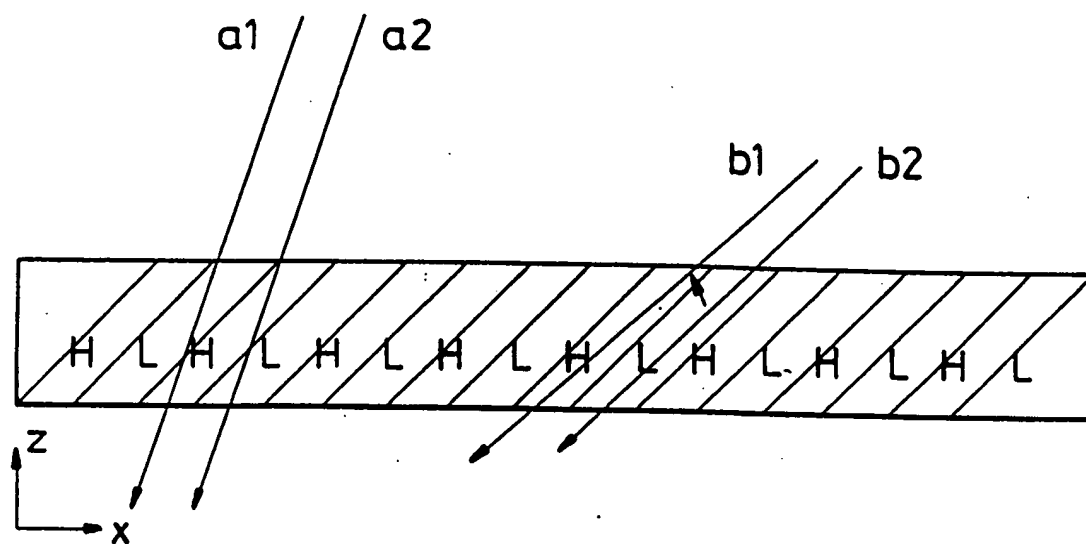
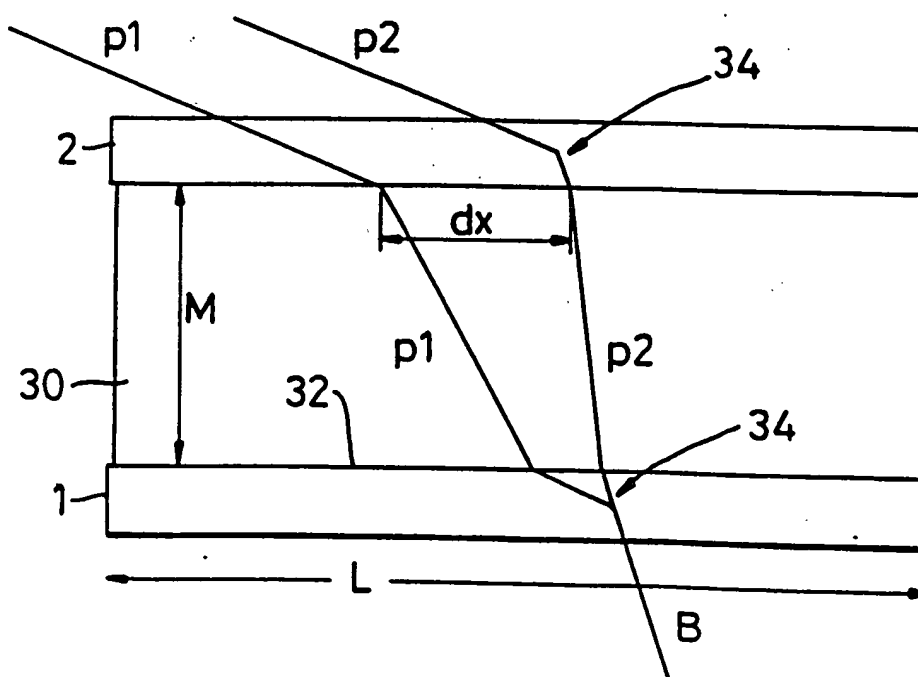
34 19. An optical device comprising a first diffraction  
35 grating for receipt of an incident optical beam  
36 comprising light having a narrow spread of frequency



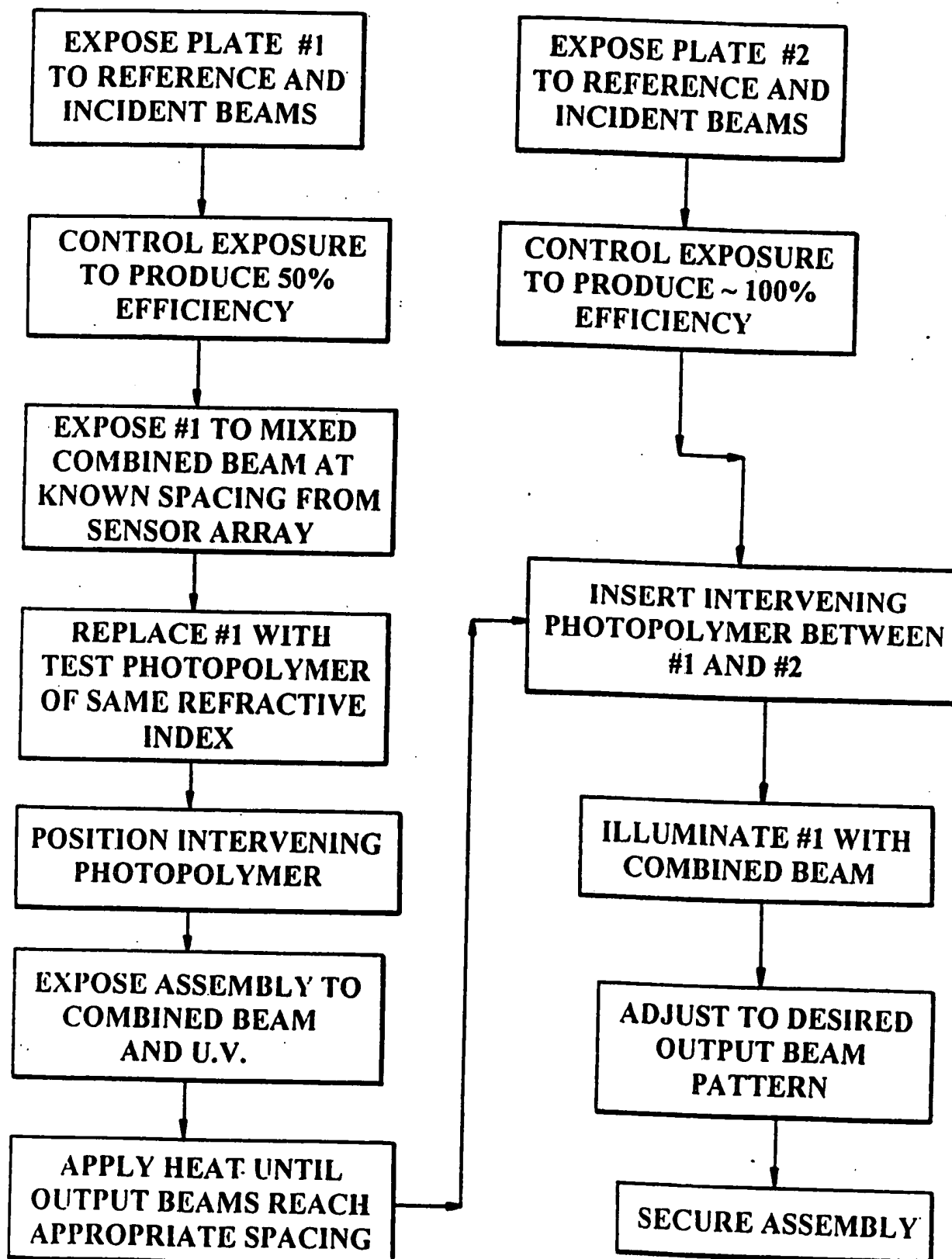
1     around a centre frequency, a second diffraction grating  
2     spaced from and parallel to the first diffraction  
3     grating, and an intermediate optical medium occupying  
4     the space between the first and second diffraction  
5     gratings; the diffraction gratings being such, and the  
6     thickness and refractive index of the intermediate  
7     optical medium being such, that the incident beam is  
8     formed by the first diffraction grating into two beams  
9     which traverse the intermediate optical medium to  
10    impinge upon the second diffraction grating by path  
11    lengths through the intermediate optical medium which  
12    differ by some multiple of one half of the wavelength  
13    corresponding to said centre frequency, whereby output  
14    beams are produced by the second diffraction grating  
15    which are collinear but in inverse phase.

16

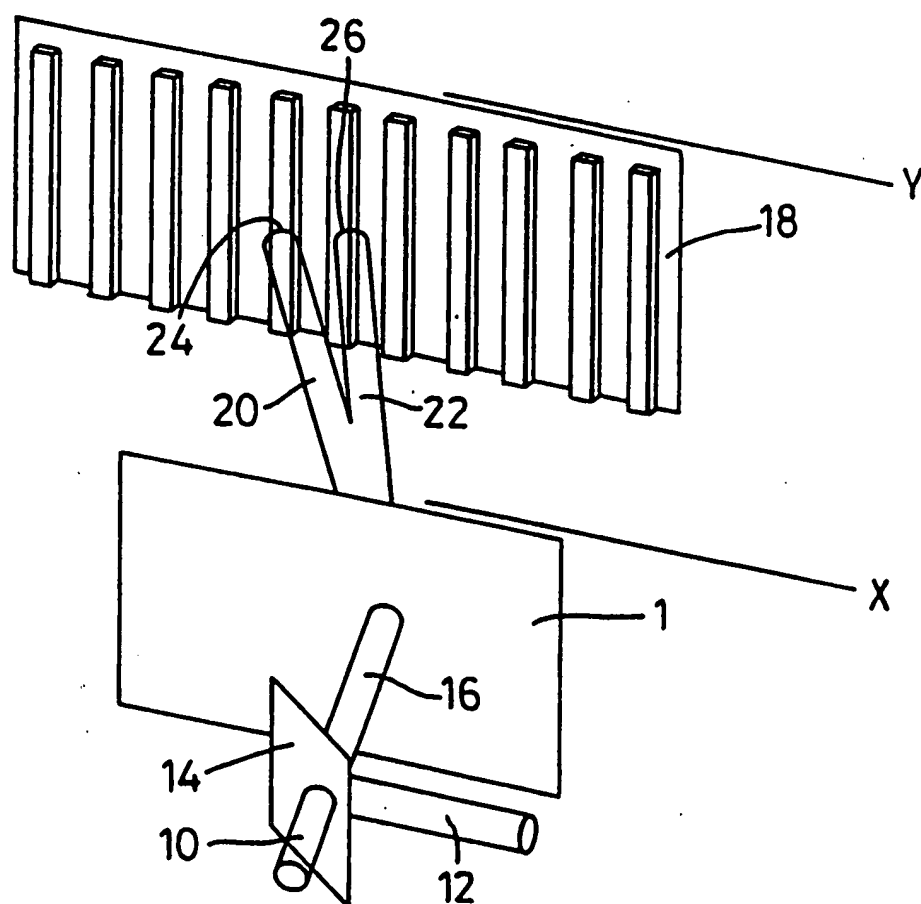
1/4

*Fig. 1**Fig. 5*

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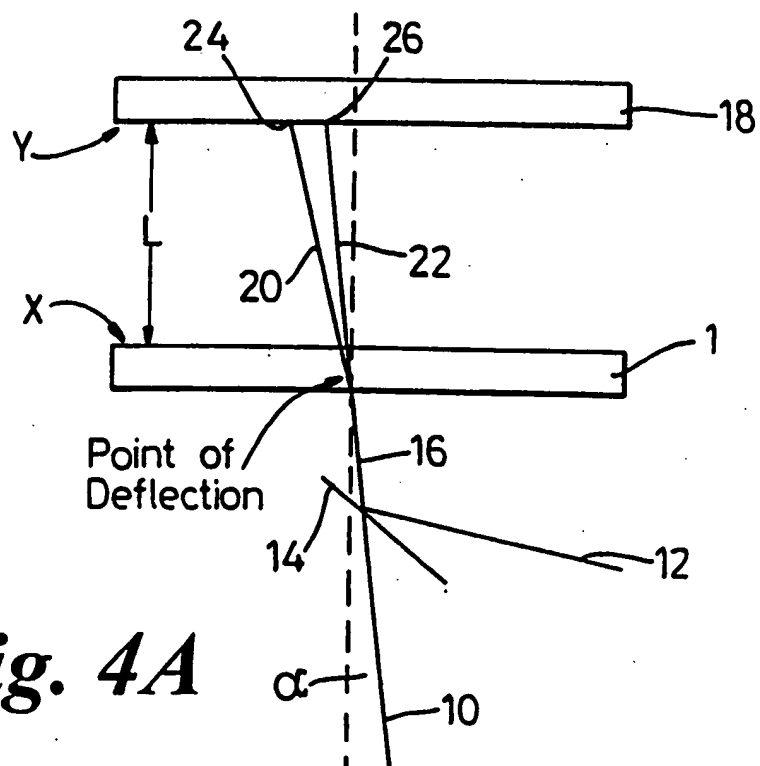
*Fig. 2*

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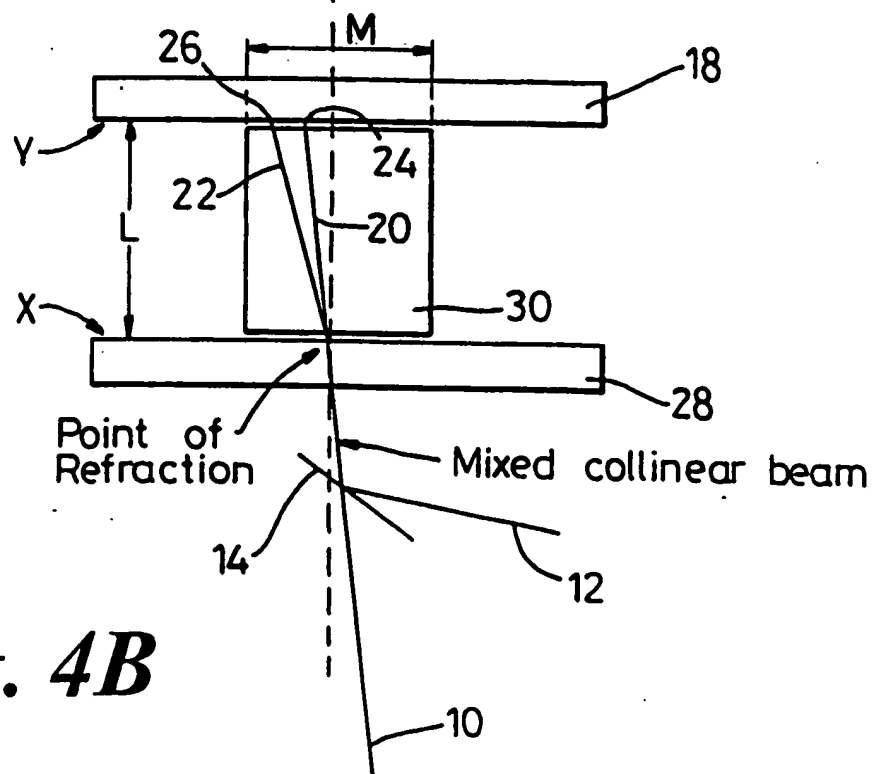


***Fig. 3***

**4/4**



***Fig. 4A***



***Fig. 4B***

# INTERNATIONAL SEARCH REPORT

Intern. Appl. No.  
PCT/GB 96/02970

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC 6 G02B5/32 G02B5/18

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)  
IPC 6 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 243 583 A (OHUCHIDA SHIGERU ET AL) 7 September 1993	1,5,12, 14,18,19
Y	see column 5, line 62 - column 6, line 22  see column 8, line 22 - column 9, line 23; claim 1; figure 6 ---	7,9-11, 13,15,16
X	US 5 071 210 A (ARNOLD STEVEN M ET AL) 10 December 1991	1,5,12, 14,18,19
Y	see column 1, line 27 - line 64  see column 3, line 4 - column 4, line 47; claims 1-7,13-18; figure 1 ---	7,9-11, 13,15,16
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Date of the actual completion of the international search

18 March 1997

Date of mailing of the international search report

- 2 05. 97

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## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 4 550 973 A (HUFNAGEL ROBERT E) 5 November 1985 see column 2, line 29 - column 4, line 50; figures 1,2  -----	15  1,5,7, 9-14,16, 18,19

# INTERNATIONAL SEARCH REPORT

International Application No

PCT/GB 96/02970

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5243583 A	07-09-93	JP 2265037 A	29-10-90
		JP 2267747 A	01-11-90
		JP 2292733 A	04-12-90
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US 5071210 A	10-12-91	NONE	
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US 4550973 A	05-11-85	NONE	
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